Status of the DARHT 2nd Axis at Los Alamos National Laboratory [*]

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Abstract

The Dual Axis Radiographic Hydrodynamic Test Facility (DARHT) was constructed at Los Alamos National Laboratory as a radiographic facility to provide two-axis multi-time radiography to support the US Stockpile Stewardship Program. The DARHT 1st Axis has been operational since 1999 and has been providing excellent radiographs. The DARHT 2nd Axis construction project was completed in early 2003. However, during the subsequent commissioning efforts to bring it to the full specifications of 18 MeV, 2 kA and 2 micro-second pulse length, high voltage breakdown was observed in several of the 78 induction accelerator cells.

In January 2004, the DARHT 2nd Axis Refurbishment and Commissioning Project was launched. It is a Los Alamos National Laboratory effort in collaboration with the Lawrence Livermore and Lawrence Berkeley National Laboratories. Its purpose is to first address the HV breakdown problems with the 2nd axis accelerator cells. A redesign of the cell is currently undergoing acceptance testing and will be discussed in companion papers presented at this conference. After the cells are refurbished and reinstalled, commissioning of the injector, accelerator and downstream transport will commence. Work is also continuing on beam transport and conversion target physics to reduce overall risk and ensure that the DARHT 2nd axis can achieve its original design goal.

The DARHT 2nd axis is scheduled for completion in early 2008, at which point the DARHT facility will be ready to support two-axis, multi-pulse radiography in support of the Stockpile Stewardship Program. In this paper, we present the overall project status, commissioning strategy and schedule.

I. Introduction

The DARHT Second Axis (Cell) Refurbishment and Commissioning Project began in Jan 2004 to remedy the accelerator cell design and assembly defects found during the commissioning of the DARHT 2nd axis accelerator. The cell problems were discovered in April 2003, after the completion of the original DARHT 2nd Axis Construction Project, as the accelerator cell voltages were being increased to their nominal operating voltage of 193 kV/cell. In addition, the project includes commissioning of the accelerator and downstream transport. This project is a collaboration among three University of California Laboratories, the Los Alamos, the Lawrence Berkeley and the Lawrence Livermore National Laboratories, with LANL having the overall project management and budgetary responsibilities.

The Dual Axis Radiographic Hydrodynamic Test (DARHT) facility, shown in Figure 1, was conceived in the early 1980's as a critical tool for nuclear weapons development and stockpile stewardship. At present, in the absence underground nuclear testing, maintenance of an aging nuclear weapons stockpile relies on complex computer simulations. The purpose of DARHT is to benchmark and verify these computer codes by providing multiple x-ray images along two axes. These images are used to evaluate the primaries of nuclear weapons through non-nuclear hydrodynamic testing, or "hydrotests". DARHT consists of two induction linear accelerators oriented orthogonal to one and other. Each accelerator generates a high current, 17 to 20 MeV electron beam. Each of these electron beams converges onto bremsstrahlung targets, which convert a fraction of the electron beam kinetic energy into x-rays. Multiple x-ray pulses are then used to image the imploding device onto

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14. ABSTRACT

The Dual Axis Radiographic Hydrodynamic Test Facility (DARHT) was constructed at Los Alamos National Laboratory as a radiographic facility to provide two-axis multi-time radiography to support the US Stockpile Stewardship Program. The DARHT 1st Axis has been operational since 1999 and has been providing excellent radiographs. The DARHT 2nd Axis construction project was completed in early 2003. However, during the subsequent commissioning efforts to bring it to the full specifications of 18 MeV, 2 kA and 2 micro-second pulse length, high voltage breakdown was observed in several of the 78 induction accelerator cells.

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detectors to produce "quasi- 3 dimensional" radiographic images.

Figure 1. Aerial view of the Dual Axis Hydrodynamic Test (DARHT) facility at the Los Alamos National Laboratory.

Flash radiography measurements require 3 essential capabilities: high resolution, multiple views for "quasi-3D" reconstruction, and multi-time frames for dynamic code benchmarking. This is illustrated schematically in Figure 2. When completed, the DARHT facility will be the first to provide this capability.

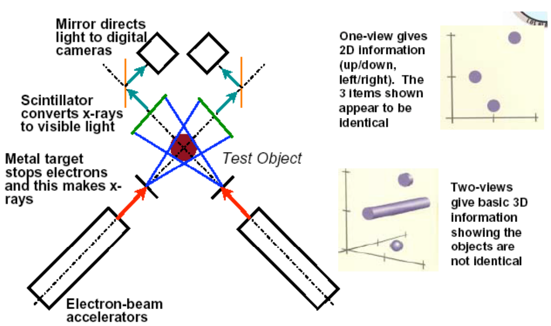

Figure 2. DARHT's dual axes design is based on generating "quasi-3D" x-ray images.

A. DARHT 1st Axis

The DARHT 1st axis [1] has been operational since 1999 and provides a single, high-resolution radiograph. The DARHT 1st axis accelerator consists of a 3 MV, 1.9 kilo-ampere electron injector having a 60 nanosecond pulse duration and 64 accelerator cells that operate at 250 kV/cell, producing a final beam energy of 19 MeV. The 1st axis accelerator cells, installed in one wing of the DARHT facility is shown in Figure 3. The 1.9 kA, 60 ns electron beam is focused to less than 2.0 mm in diameter (MTF) onto a Tantalum converter target, generating an x-ray fluence of 625 Rad at one meter. During the later part of the original DARHT 2nd Axis Construction Project and throughout the current DARHT 2nd Axis (Cell) Refurbishment and Commissioning Project, the DARHT facility, utilizing the 1st axis, has been and will continue to be a fully functioning radiographic capability in support of the US National Hydrotest Program for Stockpile Stewardship.

Figure 3. The DARHT 1st axis accelerator consists of a 3 MV injector and 64 induction cells, each cell operating at 250 kV to produce a 19 MeV, 1.9 kA, 60 ns electron beam. The electron beam is focused onto a Tantalum target, generating a 625 Rad x-ray pulse having a spot size diameter of less than 2.0 mm (MTF).

B. DARHT 2nd Axis

The DARHT 2nd axis accelerator is a 17 MeV, 2.0 kilo-Ampere, 1.6 micro-second linear induction accelerator and is shown in Figure 4. The operational parameters of the2nd axis are given Table 1. The DARHT 2nd axis accelerator consists of a 2.5 MV injector and 6 injector cells each operating at 175 kV and 68 accelerator cells each operating at 200 kV. The injector cells have a larger diameter bore compared to the accelerator cells to allow for a larger acceptance of the beam from the injector at

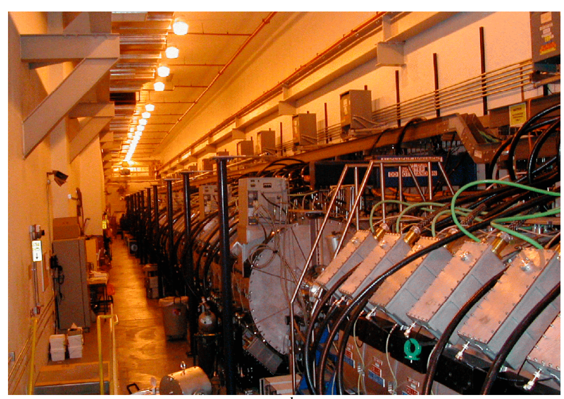

Figure 4. The DARHT 2nd axis accelerator consists of a 2.5 MV injector and 6 injector cells each operating at 175 kV and 68 accelerator cells each operating at 200 kV to produce a 17 MeV, 2.0 kA, 1.6 microsecond electron beam.

the lower energies. An electromagnetic kicker, in the downstream transport section located at the exit of the accelerator alternately diverts the electron beam to the

target and beam dump at pre-selected time intervals to produce four electron beam pulses. The four pulses are then focused onto an x-ray converter target to generate the four x-ray output pulses while the remaining beam current is transported to a graphite-tungsten beam dump. This alternate diversion of the beam is schematically shown in Figure 5. The downstream transport section has been extensively tested on LLNL's ETA-II accelerator. This work is discussed by F. W. Chambers, et al, [2] in an accompanying paper to this conference.

Table 1. DARHT 2nd Axis Performance Requirements

Injector Voltage	2.5 MV
Injector Current	2.0 kilo-Amperes
Injector Pulse Length	1.6 micro-seconds
Number of Injector Cells	6 @ 175 kV/cell
Number of Injector Cells	68 @ 200 kV/cell
Total Beam Energy	17.1 MeV (goal 18.1 MeV)
Number of Pulses	4
X-ray Output	100, 100, 100, 300 Rads @ 1 meter
X-ray Spot Size (MTF)	<2.3 mm diameter (all pulses)

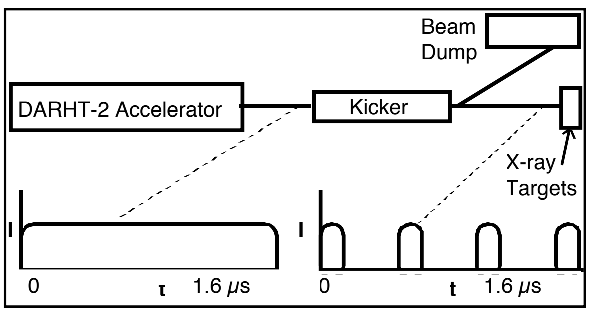

Figure 5. An electromagnetic kicker, at the exit of the accelerator alternately diverts the electron beam to the target and beam dump to produce the four electron beam pulses. The four pulses are then focused onto an x-ray converter target to generate the four x-ray output pulses.

The original DARHT 2nd Axis Construction Project completion was defined as the delivery and installation of all accelerator hardware and the delivery of all of the down stream hardware. The completion requirements for the accelerator performance were specified as: a beam current of greater than 1.0 kA; a beam energy of >12 MeV; and a beam energy pulse "flat-top" portion of 400 ns +/–50ns. These performance requirements were met in December 2002. Full commissioning efforts outside the scope of the construction project where planned to bring the accelerator to the full operating parameters of 18 MeV, 2 kA and 2 μs. That also included installation and commissioning of the downstream transport multi-pulse kicker and target. However, during commissioning, while attempting to raise the accelerator energy, high-voltage breakdown in the accelerator cells was observed and an R&D program was initiated to understand the causes and find the remedy of the problem.

II. The Accelerator Cell

A. The DARHT 2nd Axis Accelerator Cell

In December of 2002, the DARHT second axis project commissioning goals were met by demonstrating transport of a 12.25 MeV, 1.25 kA, 400 ns electron beam through the accelerator, successfully fulfilling the original construction project requirements. These goals were achieved by operating the accelerator cells at an average voltage of 138 kV. During the initial attempts to increase the cell operating voltage from 138 kV to their full operating voltage of 193 kV, several of the acceleration and injector cells experienced high-voltage breakdown.
An effort was immediately undertaken in the spring of 2003 to understand the source of the high voltage breakdown problems and to fix them. The present modified cell design is the culmination of that effort.

Four major shortcomings of the original cell design were identified:

1. Non-uniform electric field distribution in the oil-filled magnetic core region resulting in unacceptably high electric field at the outer radial edge of the magnetic cores.

2. Electric field orientation at the surface of the high-voltage vacuum insulator in the vicinity of the cathode triple point resulted in surface flashover across the vacuum insulator surface.

3. Significant voltage reversal at the end of the pulse due to core saturation resulted in flashover across the vacuum insulator surface.

4. High-voltage breakdown occurred in the oil along the surface of the "hockey puck" insulators that separate the HV drive plate from the cell ground.

The redesign of the cell (see Figure 6) corrected all of these deficiencies and are summarized below and discussed in detail, by K. E. Nielsen, et al. [3], and T. P. Hughes, et al. [4], in accompanying papers to this conference.

1. Extending the length of each cell by 2.5 cm to allow a more uniform distribution of the electric fields in the oil volume.

2. Modifying the geometry of the insulator in the vicinity of the cathode triple point.

3. Reducing the amplitude of the voltage reversal swing by adding a diode circuit to the cell drivers.

4. Extending and modifying the profile of the “hockey puck” insulators.

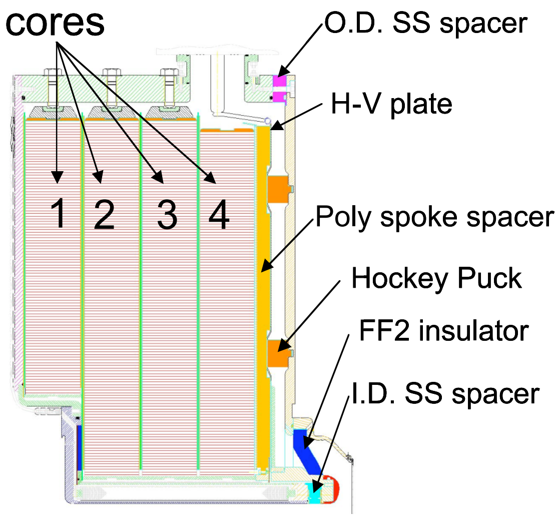

Figure 6. The cell has been redesigned to eliminate the high voltage breakdown problems experienced in the original cell design.

In addition, improved oil processing and cell component cleaning, assembly, and inspection procedures were implemented. A number of mechanical improvements were also made to the cells to improve maintenance, assembly, and reliability. This is discussed by J. Barraza, et al. [5], in an accompanying paper to this conference.

B. Prototype Acceptance Tests

A set of acceptance requirements were developed to guide prototype testing and ensure, with high confidence, that the reconfigured induction cells would meet or exceed the design voltage. These tests are discussed by W. L. Waldron, et al. [6], in an accompanying paper to this conference. The plan called for testing of six prototype (PT) cells at voltages ranging from the operating voltage of 200 to 220 kV and up to 250 kV. The total number of data shots for the six prototype cells was 190,000. Using reasonable assumptions about breakdown scaling with voltage and pulse length, this is estimated to be equivalent to about one-million shots at 200 kV with 1.5 s pulse duration. The 190,000 shots correspond to 800 firings of the complete accelerator for 3.5 times, while one-million shots corresponds to 19 such times. For the later, less than nine total failures statistically correspond to a 90% confidence level that the cells meet the “no more than one failure in 800 criterion”, which flows down from the requirement of “no more than one accelerator failure in 200 shots”.

The prototype tests were started in the summer of 2004 and were conducted at Los Alamos and Lawrence Berkeley Laboratories. The tests were highly successful. There were no high-voltage failures in any of the six PT tests. This statistically corresponds to a greater than 90% confidence level that the cells meet the reliability requirement, even if no scaling is used.

C. Cell Component Tests

In addition to the acceptance tests, a number of tests dubbed “component tests” were conducted to address specific reliability or operational issues. The components tests included:

1. "Up-to-air" cycling tests to refine requirements on vacuum region maintenance and cleaning procedures.

2. Tests with current flow down the accelerator bore to demonstrate adequacy of the ensemble of current contacts in the beamline vacuum region, with particular attention to the cell-to-cell current contact joints.

3. Tests with the cathode cap and associated mating parts fabricated at or beyond the allowable mechanical tolerance limits.

4. “End-point” high voltage bulk electrical breakdown and mechanical strength testing of the cell vacuum insulator material.

D. Re-manufacturing and Quality Control

With the completion of the cell design, the next step is to procure parts, disassemble and re-furbish the cells with the modifications, qualify the cells through high-voltage testing, and install the cells in the accelerator hall. The plan for implementing these changes on all DARHT-2 cells will utilize production processes that are modeled after “Lean Manufacturing” principles found in industry today. This process is discussed by J. Barraza, et al. [7], in an accompanying paper to this conference. As a result, new tooling, assembly techniques, and hardware have been developed, fabricated, and installed. All cells will be refurbished at Los Alamos. The Radiographic Support Laboratory (RSL) at LANL is being configured to accommodate this new tooling, with workflow divided into the appropriate independent workstations.

Quality assurance and quality control processes are an integral part of cell refurbishment. A refurbishment manual has been developed to build in quality assurance and quality control at floor level operations. This manual covers subjects such as work checklists, quality assurance and technical releases, process data records, subcomponent data records, inspections records, and acceptance criteria requirements and ensures that proper cell assembly, installation and testing of the cells occur.

III. Commissioning

Operation and commissioning of the DARHT 2nd axis will occur in three phases;

1. Beam Stability experiments – investigates the stability of long-pulse, 1.6 μs, beam transport.

2. Scaled Accelerator Validation tests – investigates the four-pulse kicker and target performance.

3. Full energy commissioning – tests and confirms performance of the completed 2nd axis accelerator, downstream transport and support systems performance.

A. Beam Stability Tests

The Beam Stability Tests address the long pulse (>1.5 μsec) beam transport stability issues, specifically Beam Break-Up (BBU) and Ion Hose instabilities. The tests do not require a high degree of cell mechanical alignment or any additional tuning of the cell pulse forming networks (PFNs) for improved voltage regulation. The beam stability test configuration, shown in Figure 7, uses 6 of the un-refurbished injector cells and 50 of the existing, un-refurbished accelerator cells. These cells are operated at 100 kV, or approximately one-half of the nominal operating voltage, in order to minimize the risk of further damage to the cells. The Beam Stability Tests are in progress and preliminary results show stable beam transport through 56 cells to a final energy of 7.3 MeV for a 1.6 μs, 1.3 kilo-ampere electron beam. The details of the accelerator operation and transport stability data are discussed in papers by B. T. McCuistian, et al [8], C. Ekdahl, et al [9], and K. C. Chan, et al [10], in accompanying papers to this conference. The Beam Stability Tests are scheduled to conclude in September 2005.

B. Scaled Accelerator Validation Tests

The Scaled Accelerator test configuration, shown in Figure 8, still uses the 6 un-refurbished injector cells, but will use 26 of the refurbished accelerator cells operated at the design voltage of 200 kV per cell. The accelerator cells will be aligned to final specifications and the cell drivers, PFNs, will be tuned to the required voltage "flat-top" of +/- 0.5%. For these validation tests, the injector, Beam Clean-Up Zone (BCUZ), and 26 cells will be operated in the final configuration. After beam transport commissioning through the 26 cells is complete, the Down Stream Transport (DST) kicker, dump and target will be tested. This will be the first test of the multi-pulse kicker and target over a full pulse duration of > 1.6 μsec to produce four pulses. Tests on LLNL's ETA-II have been conducted in support of these tests and are discussed by J. T. Weir, et al [11], and Y-J Chen, et al. [12] in accompanying papers to this conference. The Scaled Accelerator Tests will also serve as the initial test of the accelerator and Downstream Transport section as a system. The Scaled Accelerator Tests are scheduled to begin in March 2006 and continue through January 2007.

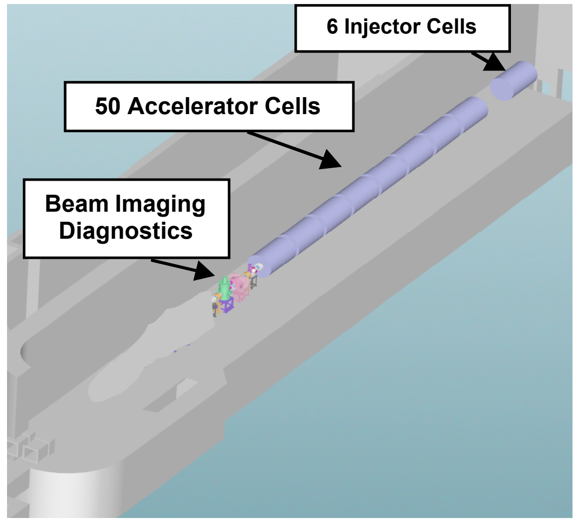

Figure 7. The Beam Stability Tests use 56 un-refurbished cells to look at long-pulse (1.6 μsec), beam transport.

At the completion of the Beam Stability and Scaled Accelerator tests, all of the physics issues associated with the beam transport, beam quality, beam centroid motion, as well as the four-pulse kicker and target performance will have been addressed, albeit, at the lower energy of ~7.5 MeV.

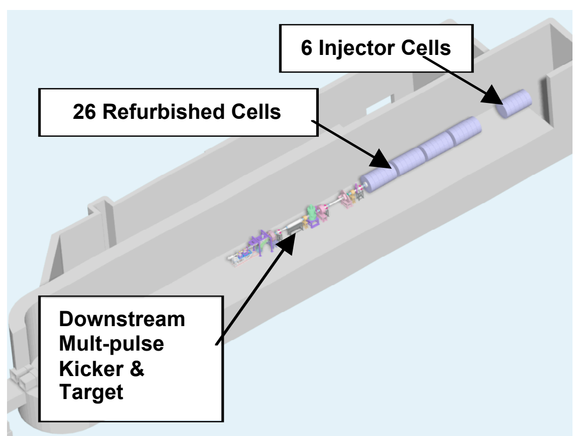

Figure 8. The Scaled Accelerator Tests will provide the first look at four-pulse kicker and target performance.

C. Full Energy Commissioning Tests

The DARHT 2nd axis accelerator is the first long-pulse, high current accelerator and, therefore, represents a considerable advancement in linear induction accelerator technology. Commissioning of the DARHT 2nd axis accelerator, kicker and target will begin in May 2007. All accelerator and downstream components will be in place and full beam energy and performance will be studied.

Figure 9 shows the diagram of the accelerator in the final configuration.

The full energy commissioning tests will conclude with the measurement of the beam x-ray dose and spot size for each of the four output pulses. At the completion of the full energy commissioning tests, the DARHT 2nd axis will be ready for integration into the DARHT facility to support the hydro-testing program.

The DARHT facility is scheduled for dual-axis, multi-pulse operation in support of the National Hydrotest Program and US Stockpile Stewardship in April 2008.

IV. SUMMARY

The DARHT 1 st axis has been operating reliably since 1999. The problems of high voltage breakdown uncovered during the initial commissioning of the DARHT 2nd axis have been identified and a modified cell design that remedies these problems has been developed and validated through an extensive test sequence. Production cell refurbishment is currently in progress.

Preliminary results of the Beam Stability Tests demonstrate that Beam Break Up and Ion Hose instabilities are well within acceptable limits. Four-pulse performance of the downstream transport kicker and target will be investigated on the Scaled Accelerator Tests that are planned to begin in early/mid 2006. The full energy commissioning of the DARHT 2nd axis is scheduled for completion in March 2008. The DARHT facility is expected to be available for dual axis, multi-pulse radiography in mid 2008.

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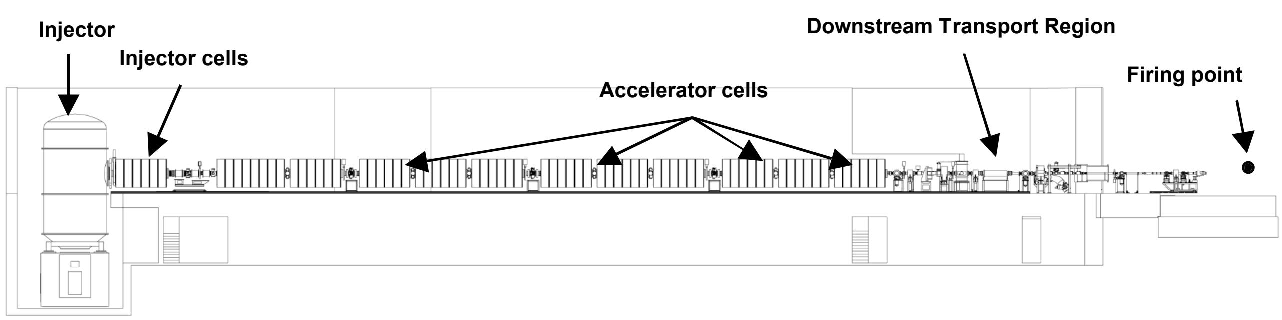

Figure 9. The DARHT 2nd axis uses a 2.5 MeV, 2 kA, 1.6 μs injector, 6 injector cells operating at 175 kV/cell, 64 accelerator cells operating at 200 kV/cell for a total beam energy of 17.1 MeV.